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Low-temperature thermochronology of the Yakutat plate corner, St. Elias Range (Alaska): bridging short-term and long-term deformation

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A B S T R A C T

This study investigates the long-term deformation and rock exhumation of the subducting Yakutat microplate corner at the St. Elias syntaxis region with a special focus on the area east and west of Yakutat Bay, where major coseismic surface uplift occurred during a M_W 8.2 earthquake in 1899. We use low-temperature thermochronology to quantify the long-term activity of thrust and reverse faults. We present new apatite and zircon (U–Th–Sm)/He ages from 35 bedrock samples collected along profiles crossing major faults that compose a one-sided flower structure at the northern end of the Fairweather Fault. The cooling ages reveal that rapid rock exhumation is accommodated by the eastern Esker Creek Fault and the Yakutat Fault with rates of 2–3 mm/yr and slower rates of <1.5 mm/yr occur along the Boundary Fault. Exceptionally high exhumation rates of 3–5 mm/yr are recorded by <1 Ma apatite ages at the western part of the Esker Creek Fault and the Chaix Hills Fault. This area is closest to the intersection line of the northwest striking reverse faults associated with the northern Fairweather Fault and the shallow dipping northeast striking thrusts of the Pamplona-Malaspina fault zone. The long-term exhumation patterns derived from this new thermochronology data are compared with the observed coseismic uplift pattern caused by the 1899 earthquake, revealing good agreement and supporting the speculation that the 1899 rupture propagated along the western part of the Esker Creek Fault and the Chaix Hills Fault. Thus, this study illustrates that low-temperature thermochronology can support seismic hazard analyses particularly in area where preservation of paleoseismic field evidence is challenged.

1. Introduction

The region where the Yakutat microplate corner collides with the North American Plate in southeast Alaska displays a complex structural setting, extremely high convergence rates, and voracious glacial erosion that combine to form the Earth's highest coastal mountain range – the St. Elias Mountains (Figs. 1 and 2). Seismic and geodetic data, together with numerical modeling reveal that crustal deformation is concentrated in two sets of tectonic structures that intersect at the St. Elias syntaxis (Fig. 2) (Elliott et al., 2010, 2013; Koons et al., 2010; Doser, 2012). Within this syntaxial region, deformation along the northwest-striking right-lateral transpressional Fairweather Fault system changes into the convergent northeast-striking thrust system of the Pamplona and Malaspina fault zone, coinciding with the highest local relief and peak elevation (Fig. 2). This setting accommodated significant crustal shortening and deformation over the past million years, which was analyzed by structural measurements in the field (Chapman et al., 2012; Pavlis et al., 2012), remote sensing (Bruhn et al., 2012; Cotton et al., 2014), and thermochronology (e.g. Berger et al., 2008; Enkelmann et al., 2009, 2010; McAleer et al., 2009; Falkowski et al., 2014).

Such a complex structural intersection zone can inhibit or delay the propagation of ruptures along major faults (King, 1983; Cotton et al., 2014), which was probably the case during the series of earthquakes occurring in September 1899 (Plafker and Thatcher, 2008). A M_W 8.1 earthquake ruptured a northeast-trending thrust fault in the Pamplona Zone, and 6 days later a M_W 8.2 earthquake occurred in Yakutat Bay area, rupturing along the northwest-trending thrust faults (Fig. 2) (Gutenberg, 1956; Doser et al., 1997). This rupture event resulted in up to 14.4 m of coseismic uplift observed along the shoreline of Disenchantment Bay and

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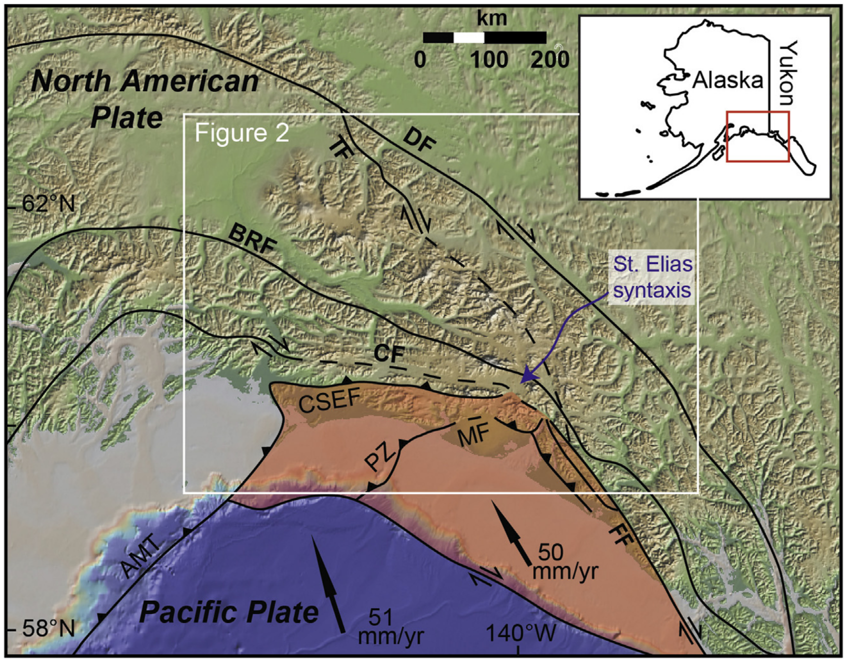

Fig. 1. Tectonic overview of southern Alaska. In red is depicted the Yakutat microplate subducting underneath North American Plate. Plate motion from Elliott et al. (2010). Also shown are major tectonic structures – CSEF: Chugach St. Elias Fault; FF: Fairweather Fault; PZ: Pamplona Fault zone; AMT: Aleutian Megathrust trench; DF: Denali Fault; CF: Contact Fault; BRF: Border Range Fault; TF: Totschunda Fault, MF: Malaspina Fault. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Russell Fjord (Taar and Martin, 1912). Fig. 3 shows the surface uplift that was carefully mapped along the shoreline, revealing the faults vertical displacement during the 1899 earthquake (Plafker and Thatcher, 2008).

The goal of this study is to bridge timescales by comparing the short-term (10^2 yr) measurements of crustal deformation – in this case a single large fault rupture in 1899 – with measurements that integrate long-term (10^5–10^6 yr) cooling of rocks during exhumation, interpreted as long-term deformation. We present new low-temperature thermochronology data (apatite and zircon (U–Th–Sm)/He ages) from bedrock samples collected in the Yakutat Bay area and along profiles crossing the faults that ruptured during the September 10 earthquake in 1899 (Fig. 3). Although thermochronology quantifies rock exhumation and not surface uplift, the very efficient erosion processes in the coastal southeastern Alaska region justify the interpretation of the differential rock exhumation across faults as proxy for fault differential displacements (e.g. Ehlers and Farley, 2003). This approach and unique geologic setting allow a comparison of the long-term rock exhumation pattern with the 1899 coseismic surface uplift pattern. We here demonstrate that thermochronologic data have the potential to reveal active faults and inform seismic hazard assessments.

2. Regional setting and background

The Yakutat microplate is a wedge shaped piece of oceanic crust that is 15–30 km thick (Christeson et al., 2010; Worthington et al., 2012). The Yakutat plate is currently moving northwest at ~50 mm/yr with respect to North America (Elliott et al., 2010) resulting in flat-slab subduction underneath southern Alaska (Plafker et al., 1994; Finzel et al., 2011). The Yakutat basement is exposed on land in the area between Seward Throat and the eastern end of Russell Fjord (study area; Fig. 3) and comprises Cretaceous-Paleocene mélange and flysch sequences that experienced a low-grade metamorphic overprint, which together form the Yakutat Group (Plafker et al., 1994). In the region west of Seward-Malaspina Glacier, the Yakutat basement is covered by up to 10 km of unmetamorphosed Cenozoic cover strata that composes the fold and thrust belt (e.g. Pavlis et al., 2004, 2012; Meigs et al., 2008; Christeson et al., 2010; Worthington et al., 2010, 2012). The Malaspina Fault, located at the western margin of the Malaspina Glacier, strikes to the northeast and constitutes the present-day deformational front of the onland fold and thrust belt (Fig. 3, e.g. Chapman et al., 2012; Pavlis et al., 2012; Van Avendonk et al., 2013). North and east of the Fairweather Fault, the North American Plate comprises igneous and metamorphic rocks of the Wrangellia Composite and Chugach terranes (e.g. Sisson and Pavlis, 1993).

2.1. Low-temperature thermochonology

Low-temperature thermochronology methods measure the time when a mineral cooled below a given (“closure”) temperature (Dodson, 1973), ranging between ca 45 °C and 350 °C (e.g. Reiners and Brandon, 2006). For most rocks, cooling to the Earth surface temperature is due to exhumation processes occurring over million-year timescales. Exhumation from deep crustal levels is the consequence of the removal of the rocks at Earth surface, and depends on the interactions between tectonic and erosional processes. In the St. Elias syntaxis, thrusts and reverse faults shorten and thicken the Yakutat crust, resulting in uplift of the upper crust by isostatic compensation. The high annual precipitation rates (5–7 m/yr) and cold climate in southeast Alaska (Gibson, 2009) result in efficient glacial erosion (e.g. Spotila et al., 2004; Koppes and Hallet, 2006). These two processes together result in rapid exhumation throughout the whole mountain range (e.g. Enkelmann et al., 2009, 2010; Spotila and Berger, 2010), and influence the isothermal structure due to thermal diffusion and differential advection of crustal material (Fig. 4, Stüwe et al., 1994; Mancktelow and Grasemann, 1997; Braun, 2002; Ehlers and Farley, 2003). In general, the isotherms are spread out more at